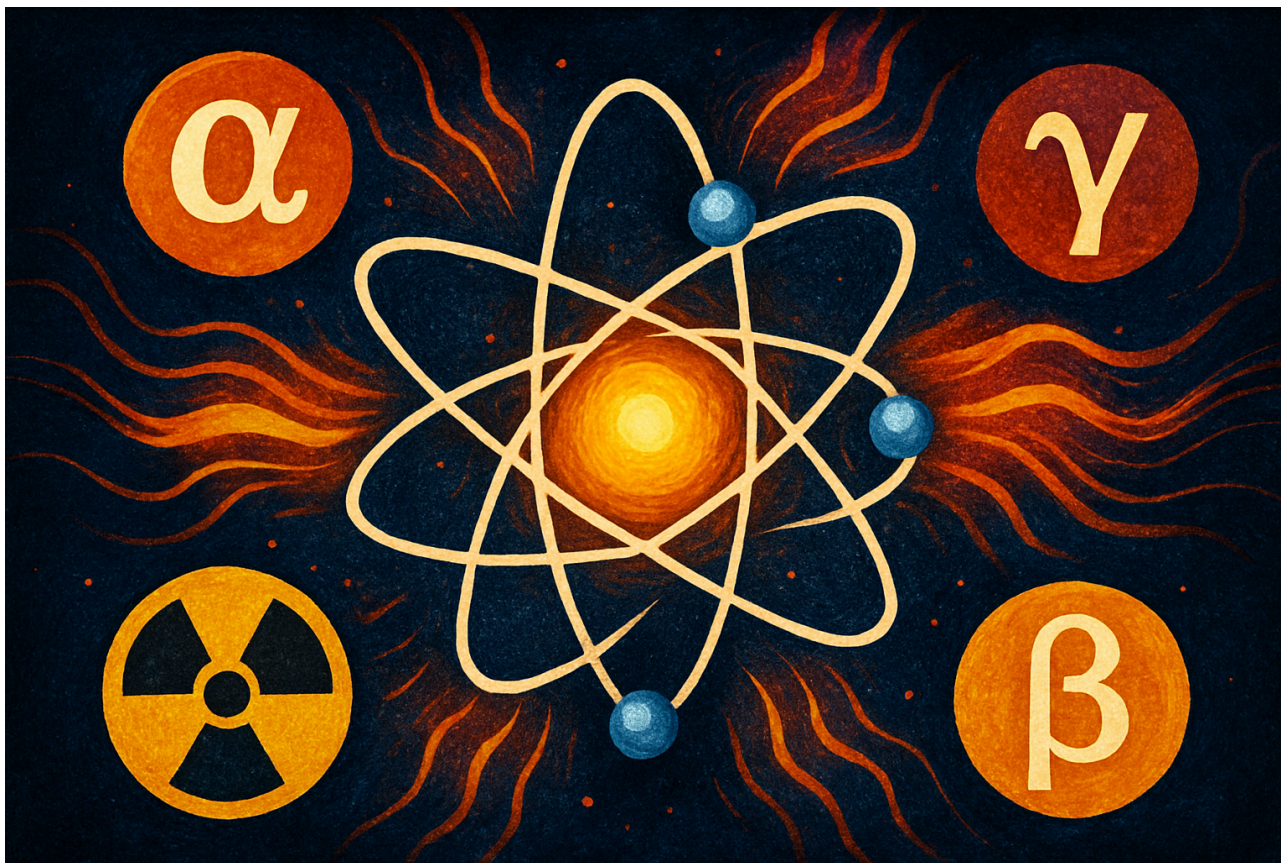# IGCSE Physics: Nuclear Physics

Syllabus Code: 0625

Learning Objectives

5.1 The nuclear model of the atom

5.1.1 The atom

- Describe the structure of an atom in terms of a positively charged nucleus and negatively charged electrons in orbit around the nucleus

- Describe how the scattering of alpha (α) particles by a sheet of thin metal supports the nuclear model of the atom, by providing evidence for: (a) a very small nucleus surrounded by mostly empty space, (b) a nucleus containing most of the mass of the atom, (c) a nucleus that is positively charged

- Know how atoms may form positive ions by losing electrons or form negative ions by gaining electrons

5.1.2 The nucleus

- Describe the composition of the nucleus in terms of protons and neutrons
- Describe the processes of nuclear fission and nuclear fusion as the splitting or joining of nuclei, to include the nuclide equation and qualitative description of mass and energy changes without values
- State the relative charges of protons, neutrons and electrons as +1, 0 and −1 respectively
- Define the terms proton number (atomic number) Z and nucleon number (mass number) A and be able to calculate the number of neutrons in a nucleus
- Know the relationship between the proton number and the relative charge on a nucleus
- Know the relationship between the nucleon number and the relative mass of a nucleus
- Use the nuclide notation Z^A X
- Explain what is meant by an isotope and state that an element may have more than one isotope

5.2 Radioactivity

5.2.1 Detection of radioactivity

- Know what is meant by background radiation
- Know the sources that make a significant contribution to background radiation including: (a) radon gas (in the air), (b) rocks and buildings, (c) food and drink, (d) cosmic rays
- Know that ionising nuclear radiation can be measured using a detector connected to a counter
- Use count rate measured in counts / s or counts / minute
- Use measurements of background radiation to determine a corrected count rate

5.2.2 The three types of nuclear emission

- Describe the emission of radiation from a nucleus as spontaneous and random in direction

- Identify alpha (α), beta (β) and gamma (γ) emissions from the nucleus by recalling: (a) their nature, (b) their relative ionising effects, (c) their relative penetrating abilities (β+ are not included, β-particles will be taken to refer to β −)

- Describe the deflection of α-particles, β-particles and γ-radiation in electric fields and magnetic fields

- Explain their relative ionising effects with reference to: (a) kinetic energy, (b) electric charge

5.2.3 Radioactive decay

- Know that radioactive decay is a change in an unstable nucleus that can result in the emission of α-particles or β-particles and/or γ-radiation and know that these changes are spontaneous and random

- Know that isotopes of an element may be radioactive due to an excess of neutrons in the nucleus and/or the nucleus being too heavy

- State that during α-decay or β-decay, the nucleus changes to that of a different element

- Describe the effect of α-decay, β-decay and γ-emissions on the nucleus, including an increase in stability and a reduction in the number of excess neutrons; the following change in the nucleus occurs during β-emission: neutron → proton + electron

- Use decay equations, using nuclide notation, to show the emission of α-particles, β-particles and γ-radiation

5.2.4 Half-life

- Define the half-life of a particular isotope as the time taken for half the nuclei of that isotope in any sample to decay; recall and use this definition in simple calculations, which might involve information in tables or decay curves (calculations will not include background radiation)

- Calculate half-life from data or decay curves from which background radiation has not been subtracted

- Explain how the type of radiation emitted and the half-life of an isotope determine which isotope is used for applications including: (a) household fire (smoke) alarms, (b) irradiating food to kill bacteria, (c) sterilisation of equipment using gamma rays, (d) measuring and controlling thicknesses of materials with the choice of radiations used linked to penetration and absorption, (e) diagnosis and treatment of cancer using gamma rays

5.2.5 Safety precautions

- State the effects of ionising nuclear radiations on living things, including cell death, mutations and cancer

- Describe how radioactive materials are moved, used and stored in a safe way

- Explain safety precautions for all ionising radiation in terms of reducing exposure time, increasing distance between source and living tissue and using shielding to absorb radiation

Core Content

5.1 The nuclear model of the atom

5.1.1 The atom

Atomic Structure: An atom consists of a central, positively charged **nucleus** surrounded by negatively charged **electrons** orbiting the nucleus. The nucleus contains **protons** (positively charged) and **neutrons** (no charge).

Rutherford's Alpha-Particle Scattering Experiment: This experiment provided crucial evidence for the nuclear model of the atom: * Most alpha particles passed straight through the thin metal foil, suggesting that atoms are mostly **empty space**. * A small number of alpha particles were deflected at large angles, and a very few were deflected straight back, indicating the presence of a **very small, dense, positively charged nucleus** at the center of the atom, containing most of its mass.

Ions: Atoms are electrically neutral (equal number of protons and electrons). However, atoms can gain or lose electrons to form **ions**: * **Positive ions:** Formed when an atom loses one or more electrons. * **Negative ions:** Formed when an atom gains one or more electrons.

5.1.2 The nucleus

Composition of the Nucleus: The nucleus is composed of **protons** and **neutrons**.

Particle	Relative Charge	Relative Mass
Proton	+1	1
Neutron	0	1
Electron	-1	1/1836

Proton Number (Atomic Number, Z): The number of protons in the nucleus. It determines the element.

Nucleon Number (Mass Number, A): The total number of protons and neutrons in the nucleus.

Calculating Number of Neutrons: Number of neutrons = A - Z

Nuclide Notation: An atom or nucleus can be represented using nuclide notation: $^{A}_{Z}X$
* X = Chemical symbol of the element * A = Nucleon number (mass number) * Z = Proton number (atomic number)

Isotopes: Isotopes are atoms of the same element (same proton number Z) but with different numbers of neutrons (different nucleon number A). For example, Carbon-12 ($^{12}_{6}C$) and Carbon-14 ($^{14}_{6}C$) are isotopes of carbon.

Nuclear Fission and Fusion: * **Nuclear Fission:** The splitting of a large, unstable nucleus (e.g., Uranium-235) into two or more smaller nuclei, releasing a large amount of energy. This process is used in nuclear power plants. * **Nuclear Fusion:** The joining of two light nuclei (e.g., isotopes of hydrogen) to form a heavier nucleus, releasing an even larger amount of energy. This process powers the Sun and other stars.

5.2 Radioactivity

5.2.1 Detection of radioactivity

Background Radiation: Background radiation is the ionising radiation that is always present in the environment from natural and artificial sources. It is important to account for background radiation when measuring the activity of a radioactive source.

Sources of Background Radiation: * **Radon gas:** Naturally occurring radioactive gas found in the air, seeping from rocks and soil. * **Rocks and buildings:** Naturally occurring radioactive elements in building materials. * **Food and drink:** Small amounts of radioactive isotopes are naturally present in our diet. * **Cosmic rays:** High-energy radiation from space that reaches Earth.

Measurement of Ionising Radiation: Ionising nuclear radiation is measured using a **detector** (e.g., Geiger-Müller tube) connected to a **counter**. The **count rate** is the number of counts detected per unit time (counts/s or counts/minute).

Corrected Count Rate: To find the true count rate from a source, the background count rate must be subtracted from the total count rate:

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Corrected Count Rate = Total Count Rate - Background Count Rate
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5.2.2 The three types of nuclear emission

Radioactive decay involves the emission of three main types of radiation:

- **Alpha (α) particles:** Consist of two protons and two neutrons (a helium nucleus). They are positively charged.
- **Beta (β) particles:** High-energy electrons emitted from the nucleus. They are negatively charged.
- **Gamma (γ) radiation:** High-energy electromagnetic waves. They have no charge and no mass.

Properties of Alpha, Beta, and Gamma Emissions:

Property	Alpha (α) particles	Beta (β) particles	Gamma (γ) radiation
Nature	Helium nucleus (^4_2He)	High-energy electron ($^0_{-1}e$)	Electromagnetic wave
Charge	+2	-1	0
Mass	Relatively heavy	Very light	No mass
Ionising Effect	Strongest	Medium	Weakest
Penetrating Ability	Weakest (stopped by paper/skin)	Medium (stopped by thin aluminium)	Strongest (stopped by thick lead/concrete)

Deflection in Electric and Magnetic Fields: * **Alpha particles:** Deflected by both electric and magnetic fields due to their positive charge. Deflection is less than beta particles due to their larger mass. * **Beta particles:** Deflected by both electric and magnetic fields due to their negative charge. Deflection is greater than alpha particles due to their smaller mass. * **Gamma radiation:** Not deflected by electric or magnetic fields as they are uncharged electromagnetic waves.

Relative Ionising Effects: * **Kinetic Energy and Charge:** Alpha particles have the highest kinetic energy and charge, causing them to collide frequently with atoms and ionise them strongly. Beta particles have less kinetic energy and charge, leading to less ionisation. Gamma rays have no charge and interact least with matter, resulting in the weakest ionisation.

5.2.3 Radioactive decay

Spontaneous and Random Decay: Radioactive decay is the process by which an unstable atomic nucleus loses energy by emitting radiation. This process is: * **Spontaneous:** It happens without any external influence. * **Random:** It is impossible to predict when a particular nucleus will decay.

Changes during Decay: * **Alpha decay:** The nucleus emits an alpha particle ($_2^4 He$). The proton number (Z) decreases by 2, and the nucleon number (A) decreases by 4. The element changes. `$_{Z}^{A}X \rightarrow _{Z-2}^{A-4}Y + _{2}^{4}He` * **Beta decay:** A neutron in the nucleus changes into a proton and an electron. The electron (beta particle) is emitted. The proton number (Z) increases by 1, and the nucleon number (A) remains unchanged. The element changes. `$_{Z}^{A}X \rightarrow _{Z+1}^{A}Y + _{-1}^{0}e` * **Gamma emission:** Often occurs after alpha or beta decay when the nucleus is in an excited state. The nucleus emits a gamma ray to lose excess energy. Neither Z nor A changes, and the element remains the same.

Isotopes and Radioactivity: Isotopes can be radioactive if they have an unstable nucleus, often due to an excess of neutrons or being too heavy. This instability leads to radioactive decay.

5.2.4 Half-life

Definition of Half-life: The **half-life** of a particular isotope is the time taken for half the nuclei of that isotope in any given sample to decay. It is a constant value for a

specific isotope and is not affected by external conditions.

Calculations involving Half-life: If a sample starts with N nuclei, after one half-life, N/2 nuclei will remain. After two half-lives, N/4 will remain, and so on.

Applications of Radioisotopes: The type of radiation emitted and the half-life of an isotope determine its suitability for various applications: * **Household fire (smoke) alarms:** Use Americium-241 (alpha emitter, long half-life) to ionise air, creating a current. Smoke disrupts the current, triggering the alarm. * **Irradiating food to kill bacteria:** Gamma rays (e.g., from Cobalt-60) are used because they are highly penetrating and can kill bacteria without making the food radioactive. * **Sterilisation of equipment:** Gamma rays are used to sterilise medical equipment as they kill microorganisms effectively without damaging the equipment. * **Measuring and controlling thicknesses of materials:** Beta emitters are used for thin materials (e.g., paper, plastic film), and gamma emitters for thicker materials (e.g., steel). The amount of radiation passing through is measured to control thickness. * **Diagnosis and treatment of cancer:** Gamma emitters (e.g., Technetium-99m for diagnosis, Cobalt-60 for treatment) are used due to their penetrating power, allowing them to reach internal organs or target cancerous cells.

5.2.5 Safety precautions

Effects of Ionising Radiation on Living Things: Ionising radiation can cause significant harm to living organisms by damaging cells and DNA, leading to: * **Cell death:** High doses can kill cells, leading to organ damage. * **Mutations:** Changes in DNA that can lead to genetic defects. * **Cancer:** Uncontrolled cell growth.

Safe Handling and Storage of Radioactive Materials: Radioactive materials must be handled, used, and stored safely to minimise exposure: * **Minimise exposure time:** Reduce the time spent near the source. * **Increase distance:** Keep as far away from the source as possible, as radiation intensity decreases with distance. * **Use shielding:** Use appropriate shielding materials (e.g., lead, concrete) to absorb radiation. * **Proper storage:** Store in lead-lined containers in secure locations.

Key Terms

- **Nucleus:** The central, positively charged part of an atom.
- **Proton:** Positively charged particle in the nucleus.

- **Neutron:** Neutral particle in the nucleus.

- **Electron:** Negatively charged particle orbiting the nucleus.

- **Proton Number (Atomic Number, Z):** Number of protons in an atom.

- **Nucleon Number (Mass Number, A):** Total number of protons and neutrons.

- **Isotopes:** Atoms of the same element with different numbers of neutrons.

- **Nuclear Fission:** Splitting of a heavy nucleus.

- **Nuclear Fusion:** Joining of light nuclei.

- **Background Radiation:** Naturally occurring radiation in the environment.

- **Count Rate:** Number of decays detected per unit time.

- **Alpha (α) particle:** Helium nucleus, +2 charge.

- **Beta (β) particle:** High-energy electron, -1 charge.

- **Gamma (γ) radiation:** Electromagnetic wave, no charge.

- **Half-life:** Time taken for half of the radioactive nuclei in a sample to decay.

Summary

This study guide has covered the fundamental concepts of nuclear physics, starting with the nuclear model of the atom, its composition, and the definitions of proton number, nucleon number, and isotopes. It then delved into radioactivity, including the detection of radiation, the properties of alpha, beta, and gamma emissions, and the principles of radioactive decay and half-life. Finally, it highlighted the important safety precautions associated with handling ionising radiation and its various applications. This knowledge forms a crucial foundation for understanding the behavior of matter at the atomic and subatomic levels.